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Antoine Clarinval and Bruno Dumas

***Abstract*—The increasing proportion of people living in urban areas causes well-known mobility issues such as pollution and congested roads. In addition to their heavy environmental impact, these issues negatively affect citizens' quality of life. Emerging technologies allow gathering huge amounts of data regarding traffic which can in turn be analyzed to diagnose mobility issues and propose solutions. Information visualization is increasingly leveraged as a medium to make the most out of this traffic data.**

In this paper, we present the systematic literature review we conducted to analyze the existing research in intra-city traffic data visualization. Following a well-defined and rigorous protocol, we have made a selection of 146 relevant works which we analyzed in depth under multiple perspectives: the data used, the domain problems, the visualization techniques and interaction, and the target end-user.

We were able to identify common practices such as the most used visualization techniques and the problems tackled the most often. This allowed us to uncover little explored research directions and to suggest avenues for innovative research. In particular, we noted a lack of visualizations engaging citizens in the reflection on mobility-related issues and a lack of consideration for user studies.

***Index Terms*—Intra-city traffic, Traffic data, Visualization, Survey, Systematic Literature Review.**

I. Introduction

The increasing urbanization reported by the United Nations [1] affects tremendously the way people move inside their city. Existing city transportation networks have to accommodate more and more passengers with often little increasing means. This causes mobility issues such as pollution and congested roads which negatively affect citizens' quality of life. New technologies allow gathering huge amounts of data regarding traffic, but this data is too voluminous and complex to be analyzed as such in an automated way [2]. Therefore, in order to make the most out of this data, information visualization proposes to integrate human users in the loop to leverage their experience and capabilities. Driven among others by the development of smart cities, many initiatives have emerged to provide visualization tools destined to experts and citizens in various domains related to intra-city traffic. Indeed, one of the main objectives of the smart city is "monitoring a city with easy-to-use visualisation tools" [3]. One prominent goal of these tools is to ensure traffic safety (i.e. the ability of individuals to travel without harm), for example by analyzing accidents [4], [5]. Another is to ensure traffic efficiency (i.e. the match between the transportation offer and citizens' demands), for example by analyzing road congestion [6]–[8]. Research on developing such tools has been plentiful in recent years, and many applications have been proposed with successful reported results.

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With this paper, we aim at providing a broad yet complete overview of the visualization tools supporting users in analyzing data related to intra-city traffic. We set the focus on the movements of a collection of human individuals at the city scale, and therefore leave areas such as vessel traffic and migration flows out of our scope. Furthermore, we set our emphasis on the techniques implemented to visualize data. Thus, although data pre-processing is an essential part of the information visualization pipeline [9], the techniques related to it will not be discussed in this paper. Instead, we set the starting point at the visualization abstraction, which is defined as "information that is visualizable on the screen using a visualization technique" [9], without discussing how this information was derived from the raw data. The research question of this article can thus be formulated as follows: **How does information visualization support intra-city traffic data analysis?**

In order to achieve the aimed overview, we devised a survey protocol following systematic review guidelines [10]–[12] that allowed collecting 146 works presenting intra-city traffic data visualization tools published in scientific conferences and journals. Information on the data sources, the domain addressed, the visualization techniques, the interactivity, the target end-user, and the conduct of user studies was extracted from each work. We report our observations for each of these six perspectives and cross them to uncover additional insights on questions such as the data sources and visualization techniques used to address a given domain. We found that most works propose expert systems supporting mobility patterns and congestion analysis. Furthermore, we discuss two research gaps identified from our analyses: a lack of research on engaging citizens in mobility-related issues through visualization and a lack of consideration for user studies.

The remaining of this paper is organized as follows. Section II brings up previous surveys on traffic data visualization and motivates the review presented in this paper. Section III frames the scope of the review and details the protocol that guided the collection and analysis of works. Section IV presents the findings for each of the six perspectives. Research gaps and connections between these perspectives are discussed in Section V. Section VI closes the paper with concluding remarks and a summary of contributions.

II. Related work

Traffic data visualization has greatly grown in importance in the past years. As a result, several works have been published to review existing research, structure the field, and propose avenues and recommendations for future research (see Table I). Five highly cited reviews are discussed below, in terms of how they classify existing research and the directions they propose. They were retrieved from a preliminary keyword search on Google Scholar and selected to cover multiple publishers.

In 2013, Andrienko and Andrienko [13] structured research on visualizing the trajectories in space and time of discrete objects. The classification scheme they proposed holds four categories, differing from each other by their perspective on movement. First, in the *looking at trajectories* perspective, trajectories are regarded as atomic constructs. The second perspective is *looking inside trajectories*, which views trajectories as a set of points and segments. The third perspective, *bird's-eye view on movement*, aggregates trajectories. Finally, the *investigating movement in context* perspective studies the links between moving objects and their environment bytes.

Two years later, Chen et al. [14] reviewed the tasks of visualization applied to traffic, the data types, the data preprocessing methods, and the visualization techniques. They proposed to structure the existing work on traffic visualization according to the represented variables into four categories. First, *time* variables represent the change over time of traffic-related constructs. Second, *space* variables describe the location in space of traffic-related constructs. The third variable type, *space-time*, combines the two previous and describes the changes over time of traffic-related constructs that have a changing location in space. Finally, the *multivariate* type refers to any variable aside time and space.

In 2016, Zheng et al. [2] presented an overview of urban data visualization. Urban data includes but is not limited to traffic data. The way they structured their review of urban data visualization is analogous to [14]. They differentiated between visualization of *time*, *location*, and *multiple properties*. The latter covers spatio-temporal properties as well as any other variable. Location data is further refined into *point-based*, *line-based*, and *region-based* data.

The following year, Andrienko et al. [15] published another survey of movement data visualization. They differentiated between *spatial event data* (i.e. data relating to a defined location in space), *trajectory data* (i.e. sequences of positions in space over time), and *space time series* (i.e. sequences of time-varying values regarding a defined location in space). Then, they organized the body of research in visualizing movement data into three categories. Unlike the classification schemes used in the other surveys brought up in this section, the categories they propose focus on why visualization is used, rather than the visualized data. First, *movement and transportation infrastructure* is concerned with understanding how the transportation infrastructure is used by travellers. Second, *movement and behavior* focuses on understanding the mobility choices of travellers as transportation infrastructure users. Finally, *modeling and planning* consists in using movement data to build predictive models.

In 2019, Sobral et al. [16] surveyed works proposing visualizations of urban mobility data destined to expert users. More specifically, they categorized the surveyed works following the domain problem they address and the data source they use. The authors proposed an extension of the data source types classification from [14].

TABLE I
FURTHER RESEARCH DIRECTIONS SUGGESTED BY PREVIOUS SURVEYS.

[13]	• Improve the collaboration between visual analytics researchers and transportation experts
[14]	• Build visualization tools that work with real-time data • Integrate heterogeneous data from different sources • Apply visual analytics on social transportation
[2]	• Visualize data sparsity and uncertainty • Integrate heterogeneous data from different sources • Improve the scalability of visualization tools • Build visualization tools following a user-centered approach • Crowdsourcing to involve more stakeholders in data analysis • Study how the combination between automated analysis and visualization can be used to improve data analysis methods
[15]	• Improve the collaboration between visual analytics researchers and transportation experts for utility and usability purposes • Stay abreast of emerging trends such as social transportation • Integrate personal preferences into navigation systems • Improve the interactivity of simulations • Develop visualizations that foster collaborative engagement
[16]	• Further study accessibility and commuting efficiency • Further exploit urban traffic conversations from social media • Further study 3D visualizations in the context of mobility • Research tools destined to help citizens in their commuting

Our research differentiates from the related work presented here in two ways. First, the process of selecting relevant works follows the widely accepted systematic literature review methodology described in [10]–[12]. Second, the classification scheme we devised for the categorization of surveyed works covers visualization, interaction, data, domain, and end-user.

III. METHODOLOGY

The main steps of the systematic literature review methodology [10]–[12] include discussing the need for a review, defining the research questions (RQ), defining a review protocol (i.e. search terms, digital libraries), selecting the relevant studies (i.e. inclusion and exclusion criteria), extracting data (i.e. extracting the relevant studies and categorization), assessing the completeness of the coverage, and describing the dissemination mechanisms. The need for a review was discussed in Section II. This section addresses the remaining steps.

A. Scope and Research Question

The objective of this work is to study how information visualization supports the analysis of intra-city traffic data by collecting and analyzing the literature relevant in this regard. In order to frame the scope of the review, definitions of traffic and of visualization are provided.

Traffic is defined as the movements of human individuals in an area. In this paper, a specific focus is put on the traffic within a city. This excludes several sub-domains from the review scope such as vessel traffic (e.g. [17]), air traffic, and movements considered on a scale larger the city such as migration flows (e.g. [18]). Following the definition of Andrienko et al. [19], we consider traffic as the movements of a collection of individuals. Regarding **visualization**, two subfields are traditionally distinguished in the literature, namely scientific visualization and information visualization [20], [21]. *Scientific visualization* consists in visualizing three-dimensional real-world entities and phenomena such as molecules and particle movement, and is therefore used when understanding shape is an important task. *Information visualization* refers to the representation of abstract and often high-dimensional data without explicit spatial reference, thus giving the designer freedom in how the space is used in the visual encoding. Traffic data is often visualized using geographic visualizations, which may appear as an ambiguous case as spatial coordinates are involved [22]. However, according to Munzner [21], the geometry can be viewed as a "backdrop against which additional information is overlaid." Therefore, traffic visualization falls within information visualization [20]. Recently, visualizations have been increasingly associated with automated data analysis techniques in a field defined as *visual analytics* [20], which is considered as a third subfield of visualization by some authors [23]. However, data analysis techniques are out of the scope of this paper, which focuses on visualization and on how it can support users in their tasks. Therefore, visual analytics works involving information visualization will be included in the review scope without considering the data analysis techniques they implement. Some authors [24] also differentiate data visualization (i.e. the use of all-purpose visualizations such as pie charts and line charts) and propose a more restrictive definition of information visualization (i.e. interactive representations that amplify cognition). In this paper, we rely on the broader definition of information visualization from [20], [21], and therefore use information visualization and data visualization as equivalent concepts.

B. Research Question Refinement and Classification Scheme

In order to answer the research question of this article, it is refined into six more specific research questions (SRQ). The refinement was guided by Munzner's What-Why-How framework [21], which formalizes visualization into three components. First, the *What* covers the data used in the visualization, which we characterize in several ways (SRQ 2). Then, the *Why* regards the problem the visualization was designed to answer, which we considered by taking an interest in the domain of traffic that is addressed (SRQ 5). The third component of Munzner's framework is the *How*, which covers the visualization techniques and the interactions. We address the visualization techniques (SRQ 3) and the interaction (SRQ 4) as two distinct SRQ. We add a fourth component, the *Who*, which relates to the end-users of the visualization. We cover this dimension by considering who are the target end-users (SRQ 1), and whether they were involved in a user-based evaluation (SRQ 6).

Below, we detail how we extracted information from the surveyed articles for each of the six SRQ. This is summarized in the classification scheme shown in Table II.

SRQ1: To which end-users are the visualizations destined? Two groups of end-users are considered, namely *Experts* and *Citizens*. The users considered as experts are those who have prior knowledge on mobility-related issues. Examples include, among others, researchers working in the field and city authorities. They interact with the visualizations in a professional context. On the other hand, citizens denote the users who do not have any particular knowledge of mobility-related issues, although they might be interested in them. Unlike experts, they encounter traffic data visualizations in a non-professional context.

SRQ2: What are the characteristics of the visualized datasets? The aim of this question is to study the features of the data from which a visual representation is generated. In particular, five characteristics of data are of interest:

- **Authenticity**: data can either be real or simulated. Real data comes from real world events and is labelled as *True*. Simulated data is mock data and is labelled as *Simulated*.
- **Source**: the source is the provider of the data. It can be *Existing data* such as mobile phone operator records or open data. Data can also come from *Citizens* via questionnaires or posts on social media for example. Another possibility is data collected using *Internet of Things* technologies such as cameras and sensors. The last possibility regards generated mock data, for which the source is labelled as *Simulated*. A clarification must be given for social media data. It is stored in the social media provider database, but has still *Citizens* as source because it is data provided by citizens on the platform, with an express will to do so. The source for phone operator data is *Existing data* because the data consists of activity records and is thus not provided explicitly as such by the operator's clients.
- **Availability**: traffic data is dynamic by nature because traffic situations evolve through time. A visualization that updates itself in response to these changes uses *Dynamic* data. On the contrary, historical data regards an elapsed timespan, and is thus not subject to changes anymore. Such data is labelled as *Static*.
- **Dimension**: traffic-related data describes in-city situations and is thus often geospatial. The dimension of data refers to the kind of geospatial object to which the data relates. Maceachren [25] distinguishes three geospatial objects, namely the *Point* which refers to a specific location in space, the *Line* which denotes connectivity, and the *Area* which represents a finite area on a map. This characteristic of data is only relevant to consider when the visualization technique used is a geospatial map.
- **Type**: the data type refers to the scale on which the data is measured. Stevens [26] lists four types of measurement scales: *Nominal*, *Ordinal*, *Interval*, and *Ratio*. The type of scale to which data belongs indicates which mathematical operations are permitted and influences the visualization techniques and visual channels used [21], [27].

Some articles mention the road infrastructure as a data source. However, in this survey, such data is not included in the data sources but is rather viewed as an overlay on which data is represented.

SRQ3: Which visualization techniques are used? The goal of this research question is to understand which visualization techniques are used in the surveyed papers. Well-known visualization techniques include, among others, the

TABLE II
CLASSIFICATION SCHEME COVERING TARGET END-USERS, DATA, VISUALIZATION, INTERACTION, DOMAIN, AND USER EVALUATION.

#	SRQ	Information	Categorization
1	End-user	Target	Citizens — Experts
2	Data	Dimension	Point — Line — Area
		Availability	Static — Dynamic
		Realness	True — Simulated
		Type	Nominal — Ordinal — Interval — Ratio
		Source	Citizens — Existing data — Internet of Things — Simulated
3	Visualization	Technique	Line chart — Bar chart — Heatmap — Parallel coordinates plot — Histogram — ...
		Map type	Dot map — Symbol map — Graduated symbol map — Network map — Ordered network map — Flow map — Colored area map — Ordered colored map — Choropleth map
		Architecture	1T — nT — 2D — 2D+1T — 2D+nT — 3D — 3D+1T — 3D+nT — 2D+3D — 2D+3D+1T — 2D+3D+nT
		Time visualiz.	Non-geospatial techniques — 3D — Animation — Time-flattening — Symbol on graduated symbol map — None
4	Interaction	ISM compliance	Yes — No
5	Domain	Domain	Mobility patterns — Congestion — Accidents — ...
6	User study	Conduct	Yes (number of participants) — No

Line chart, the *Bar chart*, the *Heatmap* (which is a term originating from a work to represent financial information in the industry, and which is distinguished here from the geospatial heatmap frequently named so in general public media), and the *Geospatial map*. A comprehensive list of visualization techniques can be found online [28]. It was used as classification baseline along with [29]. It can happen that new visualizations are created by combining several existing techniques (e.g. a pie chart with line charts drawn on the arcs to give a temporal information on the categories). In such cases, each of the existing technique composing the visualization is counted once.

As mentioned earlier, traffic-related data is often geospatial. Thus, the geospatial map technique was refined using the map type classification proposed by Unwin [30]. He presents 12 map types determined by the dimension and the measurement scale of the represented data. Point data measured on a nominal (resp. ordinal, interval/ratio) scale is represented on a *Dot map* (resp. *Symbol map*, *Graduated symbol map*). Line data measured on a nominal (resp. ordinal, interval/ratio) scale is represented on a *Network* map (resp. *Ordered network map*, *Flow map*). Area data measured on a nominal (resp. ordinal, interval/ratio) scale is represented on a *Colored area map* (resp. *Ordered colored map*, *Choropleth map*). In accordance with the definition of the choropleth map, which is to rely on a predefined spatial partitioning, choropleth maps are not restricted to administrative limits. Maps colored following a predefined grid scheme (e.g. with square or hexagon shaped cells) fall within choropleth maps as well. The three remaining map types represent volume data. These map types were not considered in this review as visualizations of spatial properties in the context of traffic are either point-based, line-based, or area-based [2], [14].

The surveyed works were also characterized by the architecture of visualization techniques they use, determined by the set of techniques integrated to constitute the proposed visualization tool. Tools can consist of 1 non-geospatial technique (*1T*), of more than one non-geospatial technique (*nT*), of only 2D maps (*2D*), of 2D maps with one other non-geospatial technique (*2D+1T*), of 2D maps with several other non-geospatial techniques (*2D+nT*), of only 3D maps (*3D*), of 3D maps with one other non-geospatial technique (*3D+1T*), of 3D maps with several other non-geospatial techniques (*3D+nT*), of 2D maps and 3D maps (*2D+3D*), of 2D maps and 3D maps with one other non-geospatial technique (*2D+3D+1T*), or of 2D maps and 3D maps with several other non-geospatial techniques (*2D+3D+nT*).

Finally, since the visual representation of time with spatial data is an important challenge for the field, we were interested in the existing approaches to represent space and time. We have listed five approaches. First, in order to represent the temporal dimension on a map, a dimension can be added. The result is a *3D visualization* where the spatial components of data are represented on the x and y axes, as a classic 2D map, and the temporal dimension is represented on the z axis. In the literature, this is referred to as the space-time cube (STC) model, which was first presented in 1970 by Hägerstand [31], who stressed the importance of analyzing human activities from a space-time point of view, and represented individual trajectories as polylines in a cube. However, the space-time cube visualization shows its limits when the number of trajectories to represent is too large [32], [33]. Several previous works addressed the issues related to the space-time cube by proposing solutions for e.g. viewpoint finding [34], [35] and supporting immersive exploration of the STC [36]. Others have represented spatio-temporal in a way that is based on the STC but aggregates trajectories to address the visual clutter issue. One technique for visually representing aggregated trajectories in the STC is stacking layers in a wall map fashion, where each layer gives average values (e.g. travel speed) for a set of trajectories [4], [7], [37]–[39]. Other techniques are isosurfaces, which consist in representing in the STC surfaces such that every point on the isosurface have a common value [7], [33], and density volume [33], which consists in coloring a volume according to the traffic density. The second approach is to combine maps with other *non-geospatial visualization techniques* able to represent the temporal dimension such as the line chart, the histogram, or the heatmap calendar view. The third approach performs *animation* of a map to display changes in time.

The fourth approach consists in relying on time flattening to represent time on 2D trajectories. Perin et al. [40] conducted an experimental study comparing different ways to encode speed and time (i.e. size, color value, and segment length) on 2D trajectories and concluded that using segment length is the best approach for encoding time on 2D trajectories. This method for representing time is named *time-flattening*. The fifth approach is somewhat similar to the combination between geospatial and non-geospatial techniques, but it relies on the *graduated symbol map* technique specifically. The symbol used on the graduated symbol map can be a visualization technique in itself able to display temporal data (e.g. line chart). For each work, we noted the methods used to represent time with spatial data. For the works not using any geospatial visualization technique, and thus not representing spatial data, the *not applicable* label was attributed. Indeed, the focus is on how the surveyed works represent both space and time visually. Other works do propose geospatial visualization but do not represent time visually and were given the label *none*. For example, these works might propose interactive time filters to allow discovering temporal patterns, but there is not any visual encoding of temporal information.

SRQ4: How is interactivity supported by the used visualization techniques? Interaction in the context of information visualization allows end-users to manipulate a visual representation according to their needs. Shneiderman [41] proposed a taxonomy including seven high-level interaction tasks, namely *Overview*, *Zoom*, *Filter*, *Details-on-demand*, *Relate*, *History*, and *Extract*. He also formulates the Information Seeking Mantra (ISM) “Overview first, zoom and filter, then details-on-demand” as guideline for interaction design. This mantra indicates that a visual interface should at first provide the user with an overview of the data at hand, then offer filtering and zooming features to allow focusing on a subset of interest, and finally give specific details on this subset. The Information Seeking Mantra is a well-established guideline in the traffic data visualization field, and was used as a guide for interaction and visual design in numerous works (e.g. [42]–[45]). Another reason for selecting the Information Seeking Mantra instead of other classifications is to evaluate the interaction aspect on the visual tool as a whole rather than on every visualization technique separately. Indeed, in some cases, an article presents a visualization tool consisting of several integrated techniques where different visualizations present information at a different level of detail. Separately, it may happen that none of them is compliant with the mantra. Still, they may together constitute a tool respecting this good practice. Since this literature review focuses on visualization rather than interaction techniques, a high-level view of interaction is kept. The focus is put on checking in a binary way whether the surveyed papers comply with the Information Seeking Mantra.

SRQ5: To which traffic-related problems do the visualizations answer? This fifth SRQ addresses the question of why a visualization was built in the first place. In traffic flow theory, and more specifically in simulation modeling, three levels are generally distinguished to represent traffic [46]. The microscopic level focuses on individual vehicles and their behavior such as lane changing. The macroscopic level aggregates the activity of the individual vehicles and characterizes traffic in terms of flow rate (i.e. the rate at which individuals reach a given location in a given timespan) and density (e.g. the number of individuals present at a given location at a given time). The mesoscopic level is a hybrid of the microscopic and the macroscopic levels.

For SRQ 5, we were however more interested in the application domains rather than the level of representation, and therefore extracted this information instead. The domains were extracted without classification scheme beforehand. They were then grouped together into ten categories following the labels attached during the review of the articles. Connections exist between the identified domains. For example, accidents cause road congestion, which in turn increases travel times and creates pollution peaks at specific areas. It can thus occur that the line of work of a paper spans several domains. When such a case occurred, each relevant domain was incremented. Some articles propose a more general solution, that is not designed to address one single class of problems. In such cases, the domains were extracted from the case studies on which the authors demonstrated their contribution.

SRQ6: Are user studies systematically conducted on the proposed visualizations? User evaluations are crucial to determine whether a visual tool is suitable to the needs and desires of the end-users it is destined to [47]. The label *Yes* is attributed to the articles that present a user study of any kind, from the informal interview with one end-user to the formal multi-user evaluation. The number of users involved, if known, is noted as well. A popular approach for validation in the field is the report of case studies conducted by the authors. However, only studies conducted with end-users fall within the scope of this SRQ. Also, some articles report end-user involvement in earlier stages, especially in defining the tasks. However, the focus is on the evaluation stage.

C. Search Terms

After defining the research question, the following step is to formulate it as a machine-understandable query in order to retrieve the relevant literature with digital libraries search engines. Petticrew and Roberts [48] proposed the PICOC (Population, Intervention, Comparison, Outcomes, Context) framework as a way to structure a query. In this survey, only the Population and the Intervention are considered, as the search query is run on the title field of the articles. The population is the application area for visualization, that is, traffic. The synonyms considered for *traffic* are *mobility*, *travel*, *accessibility*, *transport*, *transportation*, *trip*, *trajectory*, and *movement*. The intervention is what is used to address the issues described in the population, that is, the visualization. Along with *visualization* and *geovisualization*, their spelling variants *visualisation* and *geovisualisation*, and the keywords *visual* and *geovisual* are considered as well. In order to further expand the coverage, *explore* and *exploration* were added. The keywords were organized using Boolean operators, applying the PICOC framework. The following resulting search string was applied alike for the selected digital libraries:

(Traffic OR Mobility OR Travel OR Accessibility OR Transport OR Transportation OR Trip OR Trajectory OR Movement) **AND** (Visual OR Visualization OR Visualisation OR Geovisual OR Geovisualization OR Geovisualisation OR Explore OR Exploration)

D. Selected Digital Libraries

In order to gather as many of the relevant studies as possible, the aforedefined search query was applied to four prominent digital libraries, namely ACM Digital Library (ACM DL), IEEEXplore, ScienceDirect, and Wiley Online Library (WOL). This choice was driven by two reasons. First, the selected libraries, especially ACM DL and IEEEXplore, are very popular in computing-related topics [12]. Second, the selection covers both conference and journal papers.

E. Inclusion and Exclusion Criteria

Given the wide scope of the RQ, only one broad inclusion criterion is defined. Relevant research presents information visualization tools supporting intra-city traffic analysis.

The exclusion criteria defined for the survey and their rationale are as follows:

1) **Articles not written in English**.
2) **Duplicated articles**: some papers are returned by more than one of the search engines, thus leaving duplicates in the set of relevant papers. The concerned papers are considered only once, and the duplicates are removed. When two versions of the same contribution are published, only the most recent is considered.
3) **Articles published before 2008**: a time frame of 12 years is considered representative of the body of research in the field. Publications before this date are rarer and were probably superseded by more recent advances.
4) **Secondary studies**: a survey consists in a review of primary studies [10]. Secondary studies (i.e. survey contributions) gathered through the article search are covered as related work in Section II.
5) **Articles published in poster, challenge, or demo tracks**: these articles are very short and usually present research that is at a preliminary stage, and therefore do not provide the information needed for applying the classification scheme correctly.
6) **Articles that do not provide any figure representing the proposed visualizations**: the analysis of visualization techniques is part of our classification scheme. Having no figure at hand would thus hinder the correct analysis.
7) **Articles proposing visualizations not directly destined to any end-user**: some articles present visualizations of traffic data that are not destined to be used afterwards by any end-user. It is the case when the authors use information visualization as a means of sharing their findings on a research question unrelated to visualization. These were excluded, as this survey focuses on visualizations destined to end-users. Some articles discuss visualization techniques that can be applied to traffic data, but do not provide an implemented system actually destined to be used. These were excluded for the same reason.

TABLE III
NUMBER OF RELEVANT STUDIES PER DIGITAL LIBRARY (SNOWBALL ANALYSIS NOT INCLUDED).

Digital library	Articles returned	Relevant articles	% Relevant articles
ACM DL	294	18	6.1%
IEEEXplore	867	90	10.4%
ScienceDirect	783	15	1.9%
WOL	370	5	1.4%
Total	**2,314**	**128**	**5.5%**

8) **Traffic beyond the city scale**: articles discussing traffic that goes beyond the city scale such as air, maritime, or train traffic were excluded.

F. Extraction of Relevant Works

The search yielded 3,555 papers. However, a correction had to be applied for the results returned by the ACM DL, ScienceDirect, and WOL. For these libraries, the inclusion of inflected forms of the search keywords was too permissive. For example, *mobile* and *access* were accepted as inflections of *mobility* and *accessibility* respectively. Such inflected forms modify the semantics of the search string and thus cause the search to return a large number of articles not actually matching the keywords and relating to other fields. The correction consisted in removing the concerned articles by checking their title. As a result, 1,214 articles were removed. For each of the digital libraries, some duplicates were returned. The 27 concerned articles were removed as well. Therefore, the search returned 2,314 unique articles congruent with the search string, across the four digital libraries.

The relevance of each article to the review was assessed by reading its title and abstract. Table III shows the number of articles yielded by the initial search for each digital library, as well as the amount of relevant works collected. In total, 128 primary studies constitute the body of relevant research yielded through the initial search.

In order to collect studies outside the searched digital libraries, a backwards snowball analysis (BSA) was performed on the 128 articles. Combining the search on digital libraries with snowball analysis is a recommended practice when conducting a survey, as it leads to better results [49]. The bibliography of the articles underwent the same search query as the digital libraries. Also, as the goal of this survey is to provide a representative vision of the field, the articles that appeared in 5 bibliographies or more were considered, regardless of whether their title is congruent with the keywords. This allowed some mitigation of the title field limitation by including several additional works. The process yielded 70 distinct relevant papers, most of which (52) were already included in the initial pool of articles. The 18 works that were not captured by the initial search were added to the review body, thus amounting to 146 works. A second BSA on these 18 articles yielded no additional relevant work. Table VII in the supplementary material lists the 146 relevant articles returned through the search on the digital libraries and the BSA.

G. Categorization Process

The authors of the surveyed papers were not contacted for the categorization process. The information relating to the six SRQ was extracted from the papers by two researchers. Each of them read the paper independently and the results were then confronted for each paper. Disagreements were solved by discussing until reaching a consensus. Although involving only two researchers in the categorization is a limitation, it was mitigated by performing retest (i.e. second reading and categorization) on a large part of the surveyed articles, thus ensuring consistency in the categorization.

For each article, the categorization was guided by the categories defined for the SRQ, and information was collected by looking for explicit mentions in the manuscript. Information was also collected from the figures for SRQ 3 and SRQ 4 (e.g. a filtering widget on the interface screenshots indicates that the *zoom and filter* part of the mantra is satisfied). When a working URL pointing to the proposed system was provided by the authors of the article, it was checked in order to confirm the information collected from the manuscript. The acknowledgment part was analyzed for SRQ 2, as the data provider is acknowledged by the authors in some cases.

H. Coverage Assessment

In order to assess how complete a search strategy is, the set of articles yielded by the search has to be compared with another set of articles from the field. There are several ways to determine the latter [12], namely a restricted automated search, the knowledge of the researchers conducting the review, previous literature reviews, and constructing a quasi-gold standard. Given the number of previous literature reviews available, the chosen approach was to rely on the five literature reviews discussed in Section II.

The bibliographies of these literature reviews [2], [13]–[16] were screened and the relevance of each paper to the survey was checked. In total, 80 relevant articles were identified, composing what we refer to as the *known set*. Then, from the known set, the recall of the search strategy could be computed by checking how many of these 80 articles were returned by the search strategy. 50 of them were retrieved, resulting in a recall of 63%. Another recall was computed by weighting the articles from the known set according to the number of related reviews bibliographies they appear in. For instance, the article [38] is cited by [2], [13]–[15] and is therefore given a weight of 4. The article [50] is given a weight of 1 because it is cited only in [16]. The recall computed with the weights is 77%. These results show that some articles are not captured by the devised search strategy. Nonetheless, the most prominent articles from the field are successfully captured by the search strategy, as shown by the much higher value of the weighted recall. Since this review is a qualitative survey (thus, having a less critical completeness requirement [12]) that aims at giving a representative vision of the field, we consider that a 77% weighted recall is acceptable.

Among the 30 articles from the known set that were not captured, 5 are congruent with the search terms but are not indexed by the surveyed digital libraries, and therefore could not have been captured by the initial search. The other 25 articles were not captured because their title does not match the search terms. This suggests that searching on the title field only was the most limiting factor for the coverage. Searching on the abstract field instead would have partially mitigated this issue and returned 16 of the 25 concerned articles. However, expanding the search to the abstract field was not feasible, as the initial search would have returned over 17,000 results for the IEEEXplore search engine only.

I. Reporting the Review

In the subsequent sections of this paper, we report on the findings drawn from our survey. We successively address the six SRQ defined earlier and provide visual representations of our findings for better readability (Section IV). We also discuss research trends extracted by analyzing the connections between the SRQ as well as research gaps (Section V). Table VII in the supplementary material provides the categorization information extracted for each of the surveyed articles. A supplementary spreadsheet[1] also provides the necessary methodological details (e.g. decision for each excluded article, composition of the known set) as well as the categorization information in a more convenient format.

IV. Results

A. Target end-users (SRQ 1)

In total, 115 of the surveyed articles propose visualizations exclusively destined to experts. For citizens, this number (10) is approximately 11 times smaller. 15 articles target both citizens and experts. The 6 remaining articles do not specify whether the end-users are experts or citizens.

Figure 1 shows an example of tree visualization from [51] destined to experts. It represents multimodal trips originating from the same location and details the distribution of time between transportation modes and waiting. A circular stacked histogram allows comparing this distribution according to the time of day.

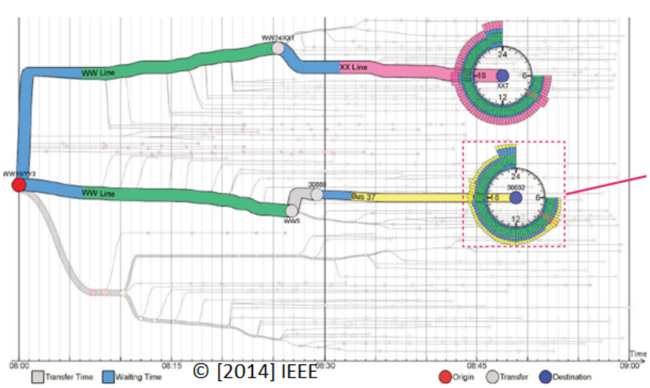

Fig. 1. Tree visualization representing the distribution of time between transportation modes and waiting of multimodal trips originating from a given location. A circular stacked histogram allows comparing this distribution according to the time of day (reproduced from [51]).

[1]https://doi.org/10.5281/zenodo.4287513

B. Data (SRQ 2)

As explained in Section III, the data used in the surveyed visualizations was considered under five aspects. In this section, the data availability, authenticity, and source are successively discussed. The data type and dimension were captured in order to refine the classification of geospatial visualizations following [30], and are therefore not addressed as such.

A first striking observation is the low amount of papers using dynamic data. Although not relevant in every work domain, dynamic traffic data remains critical for use cases such as congestion, route recommendation, and accident analysis. Still, 130 of the 146 (89%) reviewed papers use only static data. The development of more systems using real-time traffic data was stated as a recommendation for the field in [14]. However, there is no significant difference in the proportion of articles using dynamic data published per year.

With regard to the authenticity of the data, it can be observed that a large majority of the articles use true data (136 papers, 7 of which using also simulated data). This suggests that real-world data is relatively easy to obtain for research purposes. Following our classification scheme, true data has three possible sources, namely citizens, IoT, and existing data. Data from citizens was further refined into *Transparent* for cases where citizens were involved in the data collection process (e.g. volunteered tracking) and *Non transparent* data for other cases (e.g. data collected from their social media posts). Data from the Internet of Things technologies was collected mainly from cameras and other sensors. As for the existing data sources, they are usually provided by the authorities, by a company active in the transportation sector, or by another private company such as a phone operator. Figure 2 displays the data sources along with their use frequency in the surveyed articles. The total frequency (176) exceeds the number of articles because some make use of several data sources. Each data source was counted once in this case.

Figure 2 shows that eight main true data sources are used. **Authorities** (34) possess rich data relating to the territory they govern. Recently, they have become aware of the added-value their data can bring. As a result, many open government data [52] initiatives have emerged. This is reflected in the findings of this review. Among the 6 articles collected from 2020, 2 use open data [5], [53]. Another recurring example of data provided by the authorities is taxi data [54]–[59]. **Transportation services** (24) own the richest data on the use of their services. A recurring example in literature is the Mass Rapid Transit in Singapore which collects data through their tap in and tap out system (e.g. [43], [60], [61]). **Phone operators** (15) have fine-grained information on the location of their users. In the surveyed papers, their datasets span several months, which can prove useful to, e.g., study where people travel over an extended time lapse. **Social media** (13) and **online APIs** (6) are data sources accessible online at a reduced cost. These are prominent sources for obtaining real-time data. **Sensor networks** (9) are deployable at a reasonable cost provided that they span a restricted area. There is some leeway regarding the data that can be collected and its granularity. **Volunteered tracking** (8) involves citizens in the data collection process by gathering information on their mobility activities (e.g. places visited during the day). Finally, several articles reported using data collected in the context of another **research project** (7).

TABLE IV
FREQUENCY OF MAP TYPES IN THE SURVEYED ARTICLES.

Data type	Point data	Line data	Area data
Nominal	Dot map (34)	Network map (26)	Colored area map (6)
Ordinal	Symbol map (1)	Ordered network map (11)	Ordered colored map (0)
Interval or ratio	Graduated symbol map (80)	Flow map (67)	Choropleth map (18)

C. Visualization Techniques (SRQ 3)

Geospatial maps are the most used technique in traffic data visualization. This makes sense since this data is inherently geographical. In total, 136 out of the 146 surveyed articles make use of geospatial visualization. 2D visualization is more popular than its 3D counterpart, with respectively 126 and 22 uses in the surveyed papers (12 articles use 2D and 3D geospatial visualization simultaneously). Both 2D and 3D have their pros and cons. On the one hand, 3D geospatial visualizations allow displaying the spatial and temporal components of data on a unique representation, but they are usually displayed on a 2D screen and are as such difficult to read and less effective for users to carry their tasks [62]. On the other hand, 2D geospatial visualizations often have to be combined with other visualization techniques to represent temporal aspects. Combining visualizations induces no readability problem but may hinder the overview.

We observed that maps are more frequently used with ratio data because this type of data is recurrent in many mobility-related issues (e.g. how many vehicles are there at a given location, how many people moved from an area to another). Nominal data comes in second place, as many maps only represent the spatial dimensions of data items and rely on additional techniques for other dimensions. Ordinal and interval data are scarcely used. It illustrates two distinct trends in research: representing as many data attributes as possible on a map, or representing only the spatial dimensions and relying on other techniques. Another interesting observation is that the *area* data dimension is rarely used. Table IV shows the frequency of map types in the surveyed articles. The most frequently used geospatial visualization is the graduated symbol map. Its most frequent form is the density map (e.g. [5], [58], [63]–[68]), but graduated symbol maps have also been used to represent symbols of varying size (e.g. [8], [69]–[72]) or opacity (e.g. [53], [73], [74]). Some articles also use full-fledged visualization techniques as symbols. Graduated symbols maps have been used with heatmaps [19], [45], [75], line charts [76], bar charts [77], pie charts [78], rose charts [79]–[81], area charts [82], and concentric circles [83], among others.

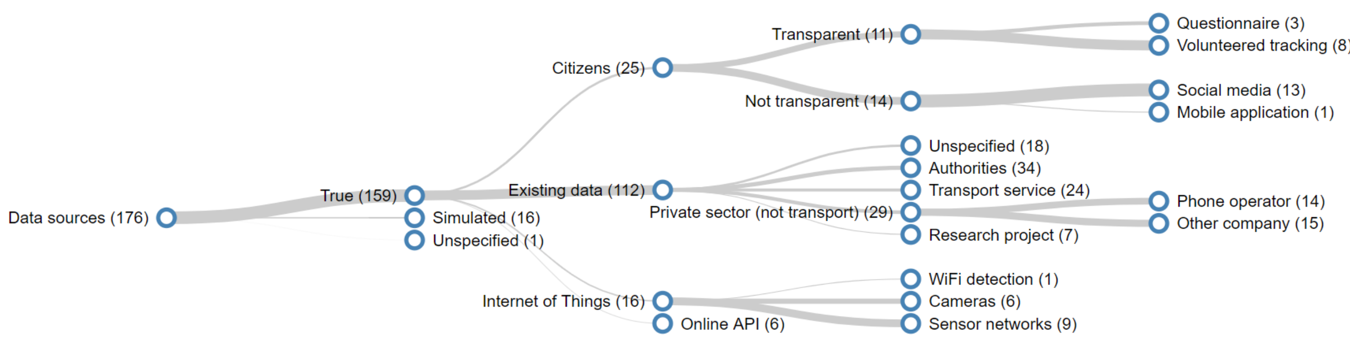

Fig. 2. Tree showing the data authenticity and sources for the surveyed articles. The number of articles using a given data source is noted in parenthesis next to the corresponding node (SRQ 2).

Figure 3 shows the visualization techniques encountered throughout the review on a node-link diagram. The size of the nodes represents the number of articles which resorted to the corresponding technique and the thickness of the links depicts the number of articles that used the connected techniques together. The techniques used in 3 articles or less are grouped together under the "other technique" label. The previously observed predominance of the 2D-geospatial visualization is startling in the display. The thickness of the links illustrates that articles often use more than one visualization technique.

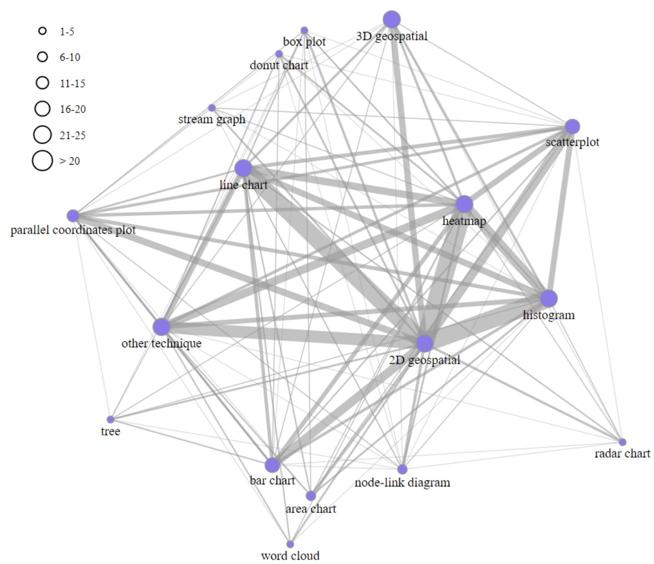

Fig. 3. Node-link diagram showing the connections between the visualization techniques. Nodes depict techniques and have a size representing the number of papers using them. Links depict connections between techniques and have a thickness representing the number of papers using both the connected techniques together (SRQ 3).

Regarding architecture, most of the surveyed works have a visualization technique architecture relying on 2D maps. The most frequent is 2D+nT, which is used in 59 out of the 146 surveyed articles. It is followed by 2D (37), 2D+1T (18), 3D (6), 1T (5), 2D+3D+1T (5), 2D+3D+nT (5), nT (5), 2D+3D (2), 3D+1T(2), and 3D+nT (2). The visualization techniques most frequently used in 2D+1T and 2D+nT architectures are the heatmap, often used as a calendar view (39), the histogram (37), the line chart (35), the scatterplot (19), the bar chart (18), and the parallel coordinates plot (14). It is interesting to note that whereas 2D maps are more often used along with other non-geospatial techniques, the most frequent architecture involving 3D maps (excluding those including 2D as well) does not include other non-geospatial techniques. This can be explained by the third dimension making it possible to represent another dimension besides space, whereas another visualization would be needed to represent the same information with a 2D map. Figure 4 shows an example of 3D-geospatial visualization from [7]. It represents the variation of congestion through time by stacking the values of each time bin on the z axis. Congestion is measured by the time needed to travel 1 kilometer. Figure 5 shows a choropleth map with a line chart from [84]. It can be seen that the map represents only the data of a limited time span. The line chart gives the whole temporal view.

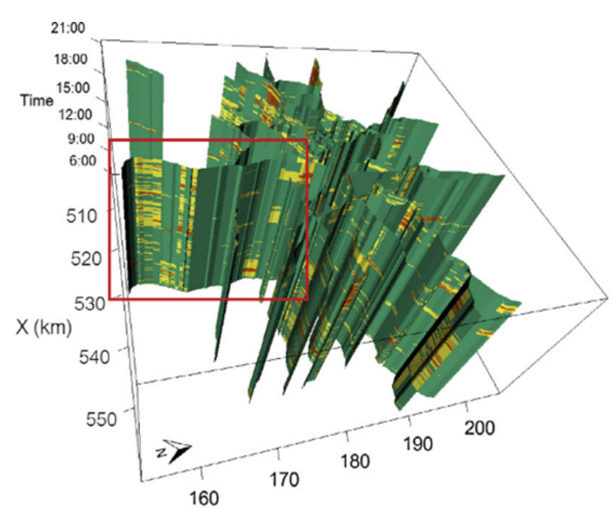

Fig. 4. 3D-geospatial visualization representing the variation of congestion through time by stacking the values of each time bin on the z axis (reproduced from [7]). Congestion is measured by the time needed to travel 1 kilometer.

The most frequent method to represent time visually is the use of non-geospatial techniques (NGT), applied in 82 of the surveyed articles. This was expected, as the most frequent architectures combine a 2D map with non-geospatial techniques. Animation (A) is supported by 19 articles and is most frequently used with 2D maps. Animation is the

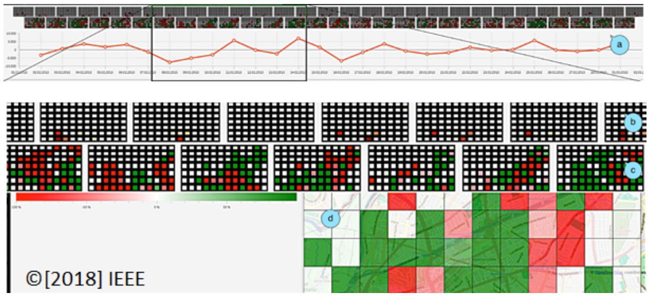

Fig. 5. Choropleth map showing data for a limited time span with a line chart giving the whole temporal view (reproduced from [84]).

TABLE V
USE OF TIME VISUAL REPRESENTATION METHODS PER VISUALIZATION TECHNIQUE ARCHITECTURE.

Architecture	NGT	3D	A	SGSM	TF	none	NA
1T	0	0	0	0	0	0	5
nT	0	0	0	0	0	0	5
2D	0	0	7	5	2	24	0
2D+1T	14	0	2	2	0	4	0
2D+nT	55	0	6	3	1	4	0
3D	0	3	1	0	0	2	0
3D+1T	2	0	1	0	0	0	0
3D+nT	2	1	1	0	0	0	0
2D+3D	0	2	0	0	0	0	0
2D+3D+1T	5	5	0	0	0	0	0
2D+3D+nT	4	3	1	1	0	0	0
Total	**82**	**14**	**19**	**11**	**3**	**34**	**10**

preferred method among articles using a 2D architecture. The third most popular method for representing time visually is using 3D. More than half of the surveyed works involving 3D in their visualization architecture use this approach. Symbols on a graduated symbol map (SGSM) are used in 11 of the surveyed articles to represent time, mainly in those relying on a 2D only architecture. Time flattening (TF) was used in only three articles. Pu et al. [85] use size and represents information in the form of an area chart displayed alongside the roads on a flow map. In [86], time is mapped to a color spectrum and portions of trajectories are colored according to the time of the day they occurred (e.g. red corresponds to 12am). In [87], bike trajectories are represented on a 2D map using a color value and size encoding. 27 of the surveyed articles use two approaches simultaneously, including most of those relying on a 2D+3D+1T or 2D+3D+nT architecture. Among the remaining works, 34 do not represent time visually, most of them not using any visualization technique besides the 2D map. Lastly, 10 articles do not use geospatial visualization techniques, and therefore were given the *not applicable* (NA) label. Table V gives the number of uses of the visual time representation approaches, for each architecture.

D. Interaction (SRQ 4)

In total, 104 of the 146 surveyed articles are compliant with the Information Seeking Mantra "Overview first, zoom and filter, then details-on-demand" [41]. Table VI provides

TABLE VI
NUMBER OF ARTICLES COMPLIANT WITH THE INFORMATION SEEKING MANTRA [41] FOR EACH END-USER CATEGORY.

Target end-users	Compliant	Not compliant
Experts only	82	33
Citizens only	7	3
Both experts and citizens	12	3
Unspecified	3	3
Total	**104**	**42**

numbers for each target end-user category. Most of the articles are compliant with the mantra, which is an encouraging result. Indeed, the presence of interaction features on visualizations allows users to make a much richer use of it.

E. Domain (SRQ 5)

In total, 10 domains characterize the surveyed research. **Mobility patterns** (73) relate to the mobility behavior of the city inhabitants and visitors, with an origin/destination view of the trips. The articles address mobility patterns under several (non exclusive) perspectives, such as the routes taken to travel from an origin to a destination [19], [57], [88], [89], the identification of origin/destination pairs regardless of the routes [54], [89]–[93], or the semantics of the origin and destination locations [73], [94]–[97]. **Congestion** (40) analysis studies questions such as the location, the magnitude, the frequency, and the reasons for occurrence of congestion events. **Microscopic movements** (13) relates to the movements of vehicles and people, regardless of the origin and destination of their trips. Examples include changing lanes on a road. **Public transportation use** (12) refers to understanding how people move with public transportation networks. **Accessibility/travel time** (12) relates to the reachability of a location, often expressed in terms of travel time. The **accidents** (10) domain refers to the analysis of traffic-related incidents such as collisions and of their impact. **Pollution** (6) covers the impact traffic has on the environment. In many cases, the impact studied relates to emissions, but other types of nuisance such as noise fall within the scope of pollution as well. **Anomaly detection** (4) refers to detecting individuals who have a mobility behavior significantly different from what is normally observed. For example, detecting pickpockets active in public transports [68]. **Route recommendation** (2) is a process taking into account various parameters and constraints to determine the optimal route between an origin and a destination. **Parking availability** (1) refers to the number of parking spots available to accommodate travelers.

Two lines of work are prominent in the surveyed articles, namely mobility patterns and congestion. The popularity of mobility patterns can be explained by the wide range of questions they allow answering. As for congestion, it is the mobility-related issue that incurs the highest financial costs, and is thus given a lot of attention. On the other hand, pollution, accessibility, and accidents are less intensively studied.

F. User study (SRQ 6)

Only 48 of the 146 surveyed papers include a user study. Out of these 48 articles, 12 do not specify the number of participants of the evaluation, 23 involved between 1 and 10 participants, and 13 evaluated their contribution with more than 10 participants.

V. Discussion

Following the analysis of the data gathered throughout the review, we were able to point out research trends and gaps in the current literature. In this section, we first address our main research question by summarizing the identified trends (Section V-A). We present an overall view on the research trends before delving deeper into the relationships between each of the perspectives (data, domain, visualization, end-user) studied in this survey. The full counts related to these discussions are provided in the tables referred to in the text, available in the supplementary material. Then, we elaborate on two under-explored research directions we believe would be beneficial to dig further (Section V-B).

A. Research Trends

1) Overall Trends: The surveyed works mainly propose expert systems allowing users to work with historical data provided by governmental authorities, public transport services, or phone operators. In most cases, one data source is used. The visualization techniques used are diversified, but the geospatial visualization is obviously prominent. It is often combined with other popular charts such as the line chart, the histogram, and the heatmap calendar view. Most of the reviewed systems comply to the Information Seeking Mantra, which seems to be a fairly established guideline in the field. The domains tackled most often include mobility patterns and congestion. Most systems did not undergo a user study, though it should be noted that illustration of the system through case studies by the authors is a popular practice. These overall trends lead to reiterate recommendations that were raised by previous surveys, such as the need for systems that integrate several data sources [2], [14] and the need to work with real-time data [14].

2) Data and Domain: The first relationship between SRQ we analyzed concerns the data sources that are used in the surveyed works to study each domain.

The data sources used to address mobility patterns are diverse. The most frequent is data from citizens (17), followed by transport services (16), phone operators (15), and authorities (14). Data from phone operators is used exclusively for the mobility patterns domain. Regarding congestion, the most frequent data source is authorities (11), with data from IoT technologies (8), transport services (7), and simulated data (7). Congestion is the domain for which IoT and simulated data are used most often. As for microscopic movements, many data sources were encountered in the surveyed works, with a similarly low frequency. The most frequent is IoT data (3), and five other sources were used twice each. As expected, the most frequent data source for public transportation use is transport services (10). Regarding accessibility/travel time, data from transport services (4) is the most frequent as well. Accidents are visualized using mainly data from authorities (7). As for pollution, simulated data is most frequently used (4), which makes pollution the domain for which simulated data is by far the most used, proportionally. Concerning anomaly detection, route recommendation, and parking availability, there is no notable insight, as these domains are addressed by very few of the surveyed works. The full counts are provided in Table VIII in the supplementary material.

3) Domain and Visualization: In order to provide more detailed insights into the visualizations that can be used to study a given domain, we have studied the connections between the visualization architecture and techniques used by the proposed tools, and the domains that these tool were designed for.

Regarding architecture (Table IX), 2D is the most popular approach for congestion (16), and 2D+nT is the most frequent for mobility patterns (37) and public transportation use (5). 2D and 2D+nT have a similar use frequency for microscopic movements (5 and 5) and accessibility/travel time (4 and 5). As for accidents, 2D+1T and 2D+nT are used 4 times each. Although few of the surveyed works analyze pollution, it was observed that 3D is as popular as 2D (2), and thus far more frequently used to study pollution than other domains.

As for geospatial visualization techniques (Table X), area-based maps are rarely used, and point-based and line-based maps have a similar use frequency. However, there are some differences across domains. Point-based is the most popular for mobility patterns and accidents. Line-based is the most popular for congestion, accessibility/travel time, and anomaly detection. Both approaches have a similar frequency for microscopic movements, public transportation use, and pollution. For accessibility/travel time, area-based maps are as frequent as point-based maps. It is the domain for which area-based maps achieve the highest proportion. On the contrary, area-based maps were encountered only once for congestion. As for the precise map types, the most frequent across all domains are the 2D graduated symbol map and the 2D flow map.

Finally, concerning non-geospatial techniques (Table XI), the most frequently encountered in the surveyed articles are the heatmap and the line chart. We observed few significant differences across domains. Yet, we noted that node-link diagrams are used almost exclusively for mobility patterns and that the parallel coordinates plot is proportionally more frequently used for mobility patterns than other domains.

4) Data and Visualization: The third relationship we studied connects the visualization techniques and the data sources. For each data source, we have listed the visualization techniques used in the surveyed works.

Concerning the architecture (Table XII), 2D+nT is the most frequent for data from authorities (16), transport services (10), phone operators (8), other private companies (8), and research projects (3). Thus, 2D+nT is the most prominent for every data source in the *Existing data* category. 2D+nT is also the most frequent architecture for data collected by Internet of Things technologies (7). As for data from citizens, 2D and 2D+nT have a similar frequency (8 and 7). Finally, 2D is the most used for simulated data (8). Simulated data is used in only 16 of the surveyed works, but still counts for half the occurrences of the 3D architecture. Proportionally, map-only architectures are much more frequent for simulated data.

Regarding geospatial visualizations (Table XIII), area-based maps are rarely used, and point-based and line-based maps have a similar use frequency, for all data sources. Point-based maps are slightly more frequent than line-based maps for data from citizens, authorities, and transport services. As for the precise map types, the most frequent across all sources are the 2D graduated symbol map and the 2D flow map.

As for the non-geospatial visualization techniques (Table XIV), the most popular are the heatmap and the line chart. There is no notable difference across data sources, except a higher prominence of the histogram for data from other private companies and for data collected by IoT technologies, and a lower proportion of heatmaps for simulated data.

5) Visualization and User: The last relationship that was studied is between the target end-users of the surveyed tools and the visualization techniques they use.

First, concerning the architecture (Table XV), the 2D approach is the most frequent in cases where citizens are included in the end-users, whereas the 2D+nT approach is much more often used for expert tools. No tool targeting citizens combines 2D and 3D maps.

Concerning geospatial visualization techniques (Table XVI), area-based maps are rarely used, and point-based and line-based maps have a similar use frequency across target users, although point-based maps are slightly more frequent than line-based ones in tools destined exclusively to experts. In addition, area-based maps are even rarer seen in works targeting citizens (used only once, compared to 20 for works including experts in their target end-users). Overall, the most frequent geospatial techniques are by far the 2D graduated symbol map and the 2D flow map. However, in tools targeting exclusively citizens, the 2D dot map and the 2D network map have a frequency similar to the 2D graduated symbol map and the 2D flow map, respectively.

Lastly, as for non-map techniques (Table XVII), the most frequent ones are the heatmap and the line chart, for both citizens and experts. Low frequencies can be observed for tools including citizens in the end-users. This is a result of the fact that the most frequent architecture for citizens involves a map without any non-geospatial visualization technique.

B. Research Gaps

1) Lack of Usability Evaluations: The involvement of transportation experts to improve the usability of systems was recommended in [15] and the wider adoption of user-centered approaches in the field was suggested in [2]. One observation that stood out from the survey is that validation and end-user involvement seem rather anchored practices in the field. However, we saw in many articles that validation is conducted via case studies only, thus without involving end-users, and that end-user involvement is often limited to defining the tasks. Indeed, in most of the surveyed works, user studies are absent, or deferred to future work (e.g. [64], [84], [88], [98]–[100]). Carrying usability evaluations is essential to assess whether an interface allows its end-users to carry their tasks in an effective and efficient way [101]. If present in these interfaces, usability issues can hinder the efficiency of the users, or even worse, prevent them from performing some tasks. If the users do not have the obligation to use the system at hand, they may also decide not use it altogether.

One reason that could explain why so few of the surveyed articles report a user study is that user studies might be tedious for researchers to integrate into their validation protocol, notably because most of them propose tools destined to professionals, and it is often challenging to obtain their time. A solution path is proposed by the human-computer interaction literature, which offers cost-efficient approaches to detect usability issues at all stages of the development. Two sets of techniques are usually distinguished: inspection techniques, which refer to those applied with usability experts, and testing techniques, which are conducted with end-users. As we focus on user studies, we restrict the discussion to testing techniques and describe some of the most popular.

Testing is conducted by asking representative end-users of the interface to use it to perform the tasks it was designed for [102]. Several techniques exist to collect usability data from users. For example, they can complete a usability questionnaire after using the system. The most widely used is the System Usability Scale (SUS) proposed by Brooke [103], which is composed of 10 questions. It has the advantage of being highly reliable and quick to complete. Research has also been conducted on interpreting [104] and deriving a learnability measure [105] from the SUS. A more recent and increasingly popular questionnaire is the User Experience Questionnaire (UEQ) [106]. It consists of 26 items measured on a Likert scale. Whereas the SUS focuses on usability, the UEQ is oriented toward user experience. An example of a more lightweight questionnaire is UMUX-LITE [107], which comprises only two items and might therefore be easier to integrate into a validation protocol.

The techniques presented here are among the most cost-efficient, and thus most popular. Many other usability evaluation techniques exist and are detailed in works such as [47] which guides designers in user-centered approaches, and [108] which details numerous reusable solutions for visualization evaluation. The techniques used should be carefully selected depending on the resources available, the current development stage, and the goals of the study, in full knowledge of the challenges specific to information visualization [109].

Another aspect that would be valuable to evaluate is the extent to which visualization good practices are respected in the surveyed works. Indeed, pitfalls of geospatial visualizations have been documented in previous literature (e.g. [110], [111]), such as the use of the red-yellow-green color scheme to represent an ordered sequential variable, appear in some of the surveyed visualizations. It would be interesting to conduct a focused analysis to identify the most frequently violated good practices and to assess their impact on the usability of the visualization through user studies. Although out of the scope of this literature review, the collected corpus of articles would constitute a strong basis to engage in this effort.

2) Lack of Visualization to Engage Citizens: Providing visual interfaces supporting transportation experts in decision-making is critical to ensure efficient traffic management, especially in larger cities. Yet, these issues are something that citizens can have an impact on, as the traffic situation is defined by the aggregated activities of all citizens. Also, citizens are willing to have opportunities to engage in these issues, as they affect their daily life. In a study [112] describing a theme-free citizen consultation process, mobility was the most recurring theme. Several analyses of citizen participation platforms also revealed that mobility is a highly popular theme for citizens to engage [113], [114].

Further research on providing tools for citizens to engage in mobility issues would thus respond to a request from the population. An interesting lead to design such tools is to rely on visualization. Indeed, previous works showed that visualization has great potential to engage citizens (e.g. [115]–[121]). Since meaningful citizen engagement involves a citizen-to-citizen dialogue, a promising approach is collaborative visualization [122], allowing several citizens to reflect on the same representation, making collective solutions and needs emerge. One recent example is a collaborative workshop supported by a city map which can be used to discuss, among others, mobility-related issues with data at hand [123].

Citizen involvement is also beneficial for the collection of traffic data. Indeed, as noted by Goodchild [124], citizens can play the role of sensors and generate data. This approach is taken by the surveyed articles using volunteered tracking and questionnaires as data sources. An example of citizens-as-sensors approach is sensing road quality [125]. However, one prerequisite to successful crowdsourcing is motivating participants [126]. One way of achieving this is to explain to them why the data they collect is valuable, which implies engaging them in the issue addressed by the crowdsourcing. In turn, citizens would be both users and co-creators of the visualizations using the collected data. This double role is recommended in the citizen involvement literature [127].

VI. Conclusion

This paper presents a broad yet complete literature review of how information visualization supports the analysis of intra-city traffic data. It is based on a sound protocol defined in line with [10]–[12]. Applying the defined review protocol allowed collecting a set of 146 articles presenting intra-city traffic data visualization tools. We extracted information from each article on the target end-users, the data used, the visualization techniques implemented, the interactivity, the domain studied, and the conduct of a user study.

We identified that the visualization tools are mostly destined to expert users who study mobility patterns or congestion using existing static data. We have also crossed the perspectives we analyzed and reported on the connections between the data sources, the domain addressed, the visualization techniques, and the target end-users. In doing so, we identified the data sources and visualizations techniques used to address given domains. Furthermore, we identified and discussed two research gaps: a lack of visualizations destined to engage citizens, and a lack of consideration for user studies.

The overview presented in this paper aims at broadness rather than depth. More focused surveys taking interest in e.g. a specific domain, or a specific range of visualization techniques, would constitute valuable contributions and provide more detailed insights into their scope. The general literature review presented in this paper constitutes a solid basis for conducting such works.

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Supplementary Material - Classification Information for the Surveyed Papers and Full Counts Related to the Discussion Section

TABLE VII: Primary studies reviewed

Ref.	Year	Publish.	Target users	Data realness	Data source	Data availability	Visualization techniques	Architecture	Time representation	Compliance to mantra	Domain	User study conduct (participants)
[8]	2011	ACM	citizens	true, simulated	citizens (volunteered tracking), simulated	static, real-time	2D dot map, 2D flow map, 2D graduated symbol map	2D	none	compliant	congestion	no
[85]	2011	ACM	unspecified	true	phone operator	static	2D choropleth map, 2D flow map, 2D graduated symbol map, histogram, line chart, mosaic plot, parallel coordinates plot, scatterplot	2D+nT	non-geospatial technique, flatten (length)	compliant	mobility patterns	no
[79]	2012	ACM	experts	true	transport service	static	2D graduated symbol map	2D	symbol on GSM	not compliant	congestion	no
[128]	2013	ACM	experts	simulated	simulated	real-time	3D flow map, 3D graduated symbol map	3D	none	not compliant	congestion, pollution	no
[70]	2014	ACM	unspecified	true	transport service	static, real-time	2D dot map, 2D graduated symbol map, 2D network map	2D	animation	compliant	public transportation use	no
[83]	2014	ACM	experts, citizens	true	authorities (public transport)	static	2D graduated symbol map, arc diagram, bubble chart	2D+nT	non-geospatial technique, animation	compliant	public transportation use	yes (27)
[129]	2015	ACM	experts	true	transport service	static	3D choropleth map, 3D graduated symbol map, histogram	3D+1T	non-geospatial technique, animation	compliant	public transportation use	yes (50)
[64]	2015	ACM	experts, citizens	simulated	simulated	static	2D graduated symbol map	2D	animation	compliant	pollution	no
[90]	2015	ACM	unspecified	true	unspecified (taxi)	static	2D choropleth map	2D	none	compliant	mobility patterns	no
[50]	2015	ACM	experts	true	authorities, transport service	static	2D choropleth map	2D	none	compliant	accessibility/travel time	yes (6)
[130]	2016	ACM	experts	true	authorities (public transport)	static	2D dot map, 2D network map, histogram, parallel coordinates plot, scatterplot	2D+nT	non-geospatial technique	compliant	public transportation use	no
[131]	2016	ACM	experts, citizens	simulated	simulated	static, real-time	2D dot map, 2D network map	2D	none	not compliant	congestion, microsc. mov.	no
[100]	2017	ACM	experts	true	citizens (questionnaire)	static	3D graduated symbol map, bar chart	3D+1T	non-geospatial technique	not compliant	mobility patterns	no
[4]	2017	ACM	experts	true	authorities	static	3D ordered network map	3D	3D	not compliant	accidents	no
[132]	2018	ACM	experts, citizens	simulated	simulated	static	3D dot map	3D	animation	compliant	microsc. mov.	yes (20)
[133]	2019	ACM	experts, citizens	true	online api (unspecified)	real-time	2D flow map	2D	none	not compliant	accessibility/travel time	no
[5]	2020	ACM	experts	true, simulated	authorities (open data), simulated	static	2D graduated symbol map, heatmap, histogram, line chart, scatterplot, sunburst diagram	2D+nT	non-geospatial technique	not compliant	accidents	no
[58]	2020	ACM	experts	true	authorities (taxi), transport service	static	2D graduated symbol map, area chart, line chart, sunburst diagram	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[19]	2008	IEEE	experts	true	authorities	static	2D flow map, 2D graduated symbol map, heatmap, stacked histogram	2D+nT	symbol on GSM, non-geospatial technique	compliant	mobility patterns	no
[134]	2009	IEEE	experts	true	authorities	static	2D graduated symbol map, bar chart, bubble chart heatmap, parallel coordinates plot, scatterplot	2D+nT	non-geospatial technique	compliant	accidents	yes (unspecified)
[135]	2009	IEEE	experts	true	authorities	static	2D dot map, 2D flow map, 2D network map	2D	none	compliant	mobility patterns	no
[136]	2009	IEEE	experts	true	authorities	static	2D dot map, heatmap, scatterplot, span chart	2D+nT	non-geospatial technique	compliant	accidents	yes (120)
[137]	2010	IEEE	experts	simulated	simulated	static	3D graduated symbol map	3D	none	not compliant	pollution	no
[138]	2010	IEEE	unspecified	true	citizens (volunteered tracking)	static	2D graduated symbol map, 3D graduated symbol map	2D+3D	3D	not compliant	accessibility/travel time, mobility patterns	no
[139]	2010	IEEE	experts	true	phone operator	static	2D graduated symbol map, 2D network map, 3D flow map, scatterplot	2D+3D+1T	non-geospatial technique, 3D	not compliant	mobility patterns	no
[140]	2011	IEEE	citizens	true	citizens (social media)	static	2D dot map, 2D ordered network map	2D	none	not compliant	congestion	no
[141]	2011	IEEE	experts	true	sensor network	static	2D flow map, 2D network map, histogram, parallel coordinates plot, scatterplot, stream graph	2D+nT	non-geospatial technique, animation	compliant	microsc. mov., congestion, mobility patterns	yes (unspecified)
[88]	2011	IEEE	experts	true	unspecified (taxi)	static	2D flow map, 2D graduated symbol map, parallel coordinates plot, stacked histogram	2D+nT	non-geospatial technique	compliant	mobility patterns, congestion, route recommendation	no

Ref.	Year	Publish.	Target users	Data realness	Data source	Data availability	Visualization techniques	Architecture	Time representation	Compliance to mantra	Domain	User study conduct (participants)
[142]	2012	IEEE	citizens	true	citizens (social media)	static	proportional area chart, scatterplot	nT	not applicable	compliant	depends what citizens publish on social media	yes (unspecified)
[143]	2012	IEEE	experts	true	cameras	real-time	2D ordered network map, bar chart, line chart	2D+nT	non-geospatial technique	not compliant	pollution	no
[39]	2012	IEEE	experts	true	authorities	static	2D flow map, 3D flow map, heatmap	2D+3D+1T	non-geospatial technique, 3D	compliant	congestion	no
[38]	2012	IEEE	experts	true	research project (taxi)	static	2D graduated symbol map, 3D flow map, heatmap, stacked histogram	2D+3D+nT	non-geospatial technique, 3D	compliant	congestion	yes (15)
[144]	2012	IEEE	citizens	true	transport service	static	3D network map	3D	3D	not compliant	accessibility/travel time	no
[63]	2013	IEEE	experts	true	sensor network	static	2D dot map, 2D graduated symbol map, area chart	2D+1T	non-geospatial technique	compliant	accidents	no
[69]	2013	IEEE	experts	true	citizens (social media)	static	2D choropleth map, 2D graduated symbol map, 2D network map, chord diagram, line chart, word cloud	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (unspecified)
[145]	2013	IEEE	citizens	true	online api (Google)	real-time	2D dot map, heatmap, word cloud	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (13)
[146]	2013	IEEE	experts	true	sensor network	static	2D choropleth map	2D	none	not compliant	pollution	no
[45]	2013	IEEE	experts	true	unspecified (taxi)	static	2D graduated symbol map	2D	symbol on GSM	compliant	mobility patterns, microsc. mov.	no
[75]	2013	IEEE	experts, citizens	true	unspecified (taxi)	static	2D graduated symbol map	2D	symbol on GSM	compliant	mobility patterns	no
[54]	2013	IEEE	experts	true	authorities (taxi)	static	2D choropleth map, 2D dot map, 2D graduated symbol map, bar chart, line chart, scatterplot	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[6]	2013	IEEE	experts	true	private company (not in the transport sector) (taxi)	static	2D flow map, 2D ordered network map, bar chart, heatmap, histogram, scatterplot	2D+nT	non-geospatial technique	compliant	congestion	no
[147]	2014	IEEE	experts	true	transport service	static	2D graduated symbol map, heatmap, line chart, scatterplot, stacked histogram	2D+nT	non-geospatial technique	compliant	microsc. mov., congestion	no
[148]	2014	IEEE	experts	true	transport service	static	line chart	1T	not applicable	not compliant	congestion	yes (unspecified)
[73]	2014	IEEE	experts	true	private company (not in the transport sector), unspecified, citizens (social media)	static	2D flow map, 2D graduated symbol map, heatmap	2D+1T	non-geospatial technique, animation	compliant	mobility patterns	no
[149]	2014	IEEE	experts	true	sensor network, unspecified	static	2D dot map, 2D ordered network map, histogram	2D+1T	non-geospatial technique	not compliant	accidents, congestion	yes (unspecified)
[150]	2014	IEEE	experts	true	private company (not in the transport sector) (taxi)	static	2D flow map, 3D area graph, 3D line chart, heatmap, scatterplot, stream graph	2D+nT	non-geospatial technique	not compliant	microsc. mov., accessibility/travel time	no
[151]	2014	IEEE	experts	true	cameras	static	2D graduated symbol map, heatmap, line chart, scatterplot, stacked histogram	2D+nT	non-geospatial technique, animation	compliant	microsc. mov., congestion	no
[152]	2014	IEEE	experts, citizens	true	transport service, citizens (social media)	static	3D flow map, heatmap, proportional area chart	3D+nT	non-geospatial technique, animation	compliant	public transportation use	no
[153]	2014	IEEE	experts	true	cameras	static	2D dot map, 2D network map, bar chart	2D+1T	none	not compliant	congestion, microsc. mov.	no
[94]	2014	IEEE	experts, citizens	true	unspecified (taxi)	static	2D flow map, line chart, parallel coordinates plot, timeline, word cloud	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[51]	2014	IEEE	experts	true	transport service	static	2D graduated symbol map, stacked histogram, tree	2D+nT	non-geospatial technique	compliant	accessibility/travel time, route recommendation	yes (2)
[154]	2015	IEEE	experts	true	phone operator, transport service	static	2D dot map, 2D flow map, 2D network map, line chart, bar chart	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (unspecified)
[91]	2015	IEEE	citizens	true	phone operator	static	2D flow map, 2D graduated symbol map, 2D network map, stacked histogram	2D+1T	non-geospatial technique	compliant	mobility patterns	no
[78]	2015	IEEE	experts	true	sensor network	static	2D graduated symbol map	2D	none	not compliant	congestion	no
[155]	2015	IEEE	experts	true	citizens (social media)	static	2D flow map, 2D graduated symbol map, heatmap, histogram, line chart, sankey diagram, word cloud	2D+nT	non-geospatial technique	compliant	mobility patterns	no

Ref.	Year	Publish.	Target users	Data realness	Data source	Data availability	Visualization techniques	Architecture	Time representation	Compliance to mantra	Domain	User study conduct (participants)
[61]	2015	IEEE	experts	true	transport service	static	3D choropleth map, 3D flow map, 3D graduated symbol map, histogram, span chart	3D+nT	non-geospatial technique, 3D	compliant	mobility patterns	no
[156]	2015	IEEE	experts	true	phone operator, citizens (social media)	static	2D flow map, 2D graduated symbol map, heatmap	2D+1T	non-geospatial technique	compliant	mobility patterns	no
[157]	2015	IEEE	unspecified	true	authorities	static	2D graduated symbol map	2D	none	not compliant	congestion	no
[158]	2015	IEEE	experts	true	phone operator	static	2D graduated symbol map, heatmap, parallel coordinates plot, sunburst diagram	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (3)
[159]	2015	IEEE	experts	true	online api (Google)	real-time	2D ordered network map	2D	none	compliant	congestion	no
[160]	2015	IEEE	experts, citizens	true	cameras	real-time	2D flow map	2D	none	compliant	congestion	no
[81]	2015	IEEE	experts	true	research project (taxi)	static	2D flow map, 2D graduated symbol map, line chart, node-link diagram	2D+nT	symbol on GSM, non-geospatial technique	compliant	mobility patterns	yes (15)
[71]	2015	IEEE	experts	true	private company (not in the transport sector) (taxi)	static	2D flow map, area chart, box plot, parallel sets, stacked histogram	2D+nT	non-geospatial technique, animation	compliant	accessibility/travel time	yes (7)
[89]	2015	IEEE	experts	true	unspecified (taxi)	static	2D graduated symbol map, histogram, line chart, parallel coordinates plot	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (3)
[80]	2015	IEEE	experts	true	authorities (open data)	static	2D flow map, 2D graduated symbol map	2D	symbol on GSM	not compliant	microsc. mov.	no
[161]	2015	IEEE	experts	true	wifi detection	static	2D dot map, 2D graduated symbol map, 2D network map, histogram, line chart	2D+nT	non-geospatial technique	not compliant	mobility patterns	no
[42]	2015	IEEE	experts	true	transport service	static	heatmap	1T	not applicable	compliant	public transportation use	yes (1)
[162]	2016	IEEE	experts	true	citizens (social media)	real-time	2D ordered network map	2D	none	not compliant	congestion	no
[163]	2016	IEEE	experts, citizens	true	private company (not in the transport sector), research project	static	2D dot map, 2D flow map, 2D graduated symbol map	2D	animation	not compliant	congestion, microsc. mov.	no
[164]	2016	IEEE	experts	true	phone operator	static	2D dot map, 2D flow map, 2D graduated symbol map	2D	none	compliant	mobility patterns	no
[56]	2016	IEEE	experts	true	citizens (social media), authorities (taxi)	static	2D choropleth map, 2D flow map, area chart, histogram, scatterplot	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[165]	2016	IEEE	experts	true	citizens (volunteered tracking)	static	2D dot map, gantt chart, heatmap	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[77]	2017	IEEE	experts	simulated	simulated	static	2D flow map, 2D graduated symbol map, 2D network map, heatmap	2D+1T	none	compliant	congestion, pollution, mobility patterns	no
[166]	2017	IEEE	experts	true	phone operator	static	2D flow map, 2D graduated symbol map, stacked chart	2D+1T	non-geospatial technique	compliant	mobility patterns	yes (2)
[167]	2017	IEEE	experts	true	authorities	static	2D flow map, 2D graduated symbol map, 2D ordered network map	2D	none	compliant	congestion, accidents	yes (6)
[168]	2017	IEEE	experts	true	research project	static	2D flow map, heatmap, heatmap, histogram, line chart, radviz	2D+1T	non-geospatial technique	compliant	accidents, microsc. mov., anomaly detection	yes (unspecified)
[169]	2017	IEEE	experts	simulated	simulated	static	2D flow map	2D	animation	not compliant	congestion	yes (1)
[65]	2017	IEEE	experts, citizens	true	transport service	static	2D dot map, 2D flow map, 2D graduated symbol map, bar chart, circle packing, donut chart, heatmap	2D+nT	none	compliant	public transportation use	no
[86]	2017	IEEE	experts	true	private company (not in the transport sector) (taxi)	static	2D flow map	2D	flatten (color)	not compliant	accessibility/travel time	no
[87]	2017	IEEE	citizens	true	authorities	static	2D flow map	2D	animation, flatten (color, size)	compliant	microsc. mov.	yes (unspecified)
[84]	2017	IEEE	experts	true	citizens (volunteered tracking)	static	2D choropleth map, 2D colored area map, 2D dot map, 3D flow map, heatmap, line chart, tree	2D+3D+nT	non-geospatial technique, 3D	compliant	mobility patterns	no
[95]	2017	IEEE	experts	true	private company (not in the transport sector)	static	2D dot map, 2D flow map, heatmap, node-link diagram, stream graph	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (10)

Ref.	Year	Publish.	Target users	Data realness	Data source	Data availability	Visualization techniques	Architecture	Time representation	Compliance to mantra	Domain	User study conduct (participants)
[170]	2017	IEEE	experts	true	private company (not in the transport sector) (taxi)	static	2D flow map, 2D graduated symbol map, bar chart, box plot, node-link diagram, parallel coordinates plot, stacked histogram, tree	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[171]	2017	IEEE	experts	true	citizens (application)	static	2D choropleth map, 2D network map, 2D symbol map	2D	none	compliant	mobility patterns	yes (2)
[172]	2017	IEEE	experts	true	citizens (social media), transport service	static	2D dot map, 2D graduated symbol map	2D	symbol on GSM	compliant	mobility patterns	yes (3)
[173]	2018	IEEE	experts	unspecified	unspecified	real-time	2D network map	2D	none	compliant	mobility patterns	no
[174]	2018	IEEE	experts	true	cameras	static	heatmap, histogram	nT	not applicable	compliant	anomaly detection	no
[175]	2018	IEEE	experts	true	unspecified	static	2D graduated symbol map, histogram	2D+1T	non-geospatial technique	compliant	parking availability	no
[57]	2018	IEEE	experts	true	authorities (taxi)	static	2D dot map, 2D flow map, 2D graduated symbol map, donut chart, heatmap, histogram, node-link diagram, scatterplot	2D+nT	non-geospatial technique	compliant	congestion, mobility patterns	yes (10)
[176]	2018	IEEE	unspecified	simulated	simulated	static	2D flow map	2D	none	not compliant	mobility patterns	no
[177]	2018	IEEE	experts, citizens	true	citizens (volunteered tracking)	static	2D graduated symbol map, line chart	2D+1T	non-geospatial technique	compliant	mobility patterns	no
[178]	2018	IEEE	experts	true	authorities	static	2D flow map, 2D graduated symbol map, heatmap, line chart, scatterplot	2D+nT	non-geospatial technique	not compliant	accidents	no
[179]	2018	IEEE	citizens	true	authorities (open data), citizens (volunteered tracking)	static, real-time	2D dot map, 2D network map, multiset bar chart	2D+1T	none	compliant	accidents	no
[180]	2018	IEEE	experts	true	phone operator, transport service	static	2D flow map, 2D network map, heatmap, histogram, multiset bar chart, radar chart	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (2)
[72]	2018	IEEE	experts	true	cameras	static	2D graduated symbol map, 2D ordered network map	2D	none	compliant	congestion	no
[181]	2018	IEEE	experts	true	sensor network	static	heatmap, histogram, proportional area chart	nT	not applicable	compliant	mobility patterns	no
[74]	2019	IEEE	experts	true	citizens (volunteered tracking), sensor network	static	2D graduated symbol map, 3D scatterplot, bar chart, line chart	2D+nT	non-geospatial technique	compliant	parking availability	no
[67]	2019	IEEE	experts	true	phone operator	static	2D colored area map, 2D graduated symbol map, node-link diagram, radar chart	2D+nT	none	compliant	mobility patterns	no
[182]	2019	IEEE	experts	true	sensor network	static, real-time	2D flow map, heatmap, histogram	2D+nT	non-geospatial technique, animation	compliant	congestion	yes (3)
[93]	2019	IEEE	experts	true	unspecified (taxi)	static	2D choropleth map, 2D flow map, 2D graduated symbol map, histogram	2D+1T	non-geospatial technique	compliant	mobility patterns	yes (35)
[183]	2019	IEEE	experts	true	unspecified (taxi)	static	heatmap, line chart, node-link diagram, stacked chart	nT	not applicable	compliant	mobility patterns	no
[184]	2019	IEEE	experts	true	citizens (questionnaire)	static	2D choropleth map, chord diagram, donut chart, heatmap	2D+nT	non-geospatial technique, animation	compliant	mobility patterns	yes (51)
[185]	2019	IEEE	experts	true	phone operator	static	2D graduated symbol map, heatmap, line chart	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (unspecified)
[59]	2019	IEEE	experts	true	authorities (taxi)	static	2D flow map, heatmap, histogram, line chart, stacked bar chart, stacked histogram	2D+nT	non-geospatial technique	compliant	congestion, mobility patterns	yes (8)
[186]	2019	IEEE	experts, citizens	true	unspecified (taxi)	static	2D colored area map, 2D flow map, 2D graduated symbol map, multiset bar chart	2D+1T	none	compliant	accessibility/travel time	yes (12)
[187]	2019	IEEE	experts	true	authorities, research project (taxi)	static	2D colored area map, 2D graduated symbol map, area chart, box plot, heatmap, line chart, multiset histogram, parallel coordinates plot, scatterplot	2D+nT	non-geospatial technique	compliant	congestion	no
[68]	2020	IEEE	experts	true	authorities (public transport)	static	2D dot map, 2D flow map, 2D graduated symbol map, 3D network map, heatmap, node-link diagram, parallel coordinates plot	2D+3D+nT	symbol on GSM, 3D	compliant	mobility patterns, anomaly detection	yes (30)
[188]	2020	IEEE	experts	simulated	simulated	static	2D dot map, 2D network map	2D	animation	compliant	congestion	yes (1)
[53]	2020	IEEE	citizens	true	authorities (open data)	static, real-time	2D graduated symbol map, bar chart, heatmap, line chart, pie chart, stacked histogram	2D+nT	non-geospatial technique	compliant	mobility patterns	no

Ref.	Year	Publish.	Target users	Data realness	Data source	Data availability	Visualization techniques	Architecture	Time representation	Compliance to mantra	Domain	User study conduct (participants)
[7]	2013	Elsevier	experts	true	authorities (cameras)	static	3D flow map	3D	3D	not compliant	congestion	no
[189]	2014	Elsevier	experts	true	transport service	static	2D flow map	2D	none	not compliant	public transportation use	no
[190]	2014	Elsevier	experts	true, simulated	private company (not in the transport sector), simulated	static	2D network map, box plot, line chart	2D+nT	non-geospatial technique	not compliant	congestion	no
[191]	2015	Elsevier	experts	true	research project	static	bar chart, heatmap, line chart, tree	nT	not applicable	compliant	congestion	yes (10)
[192]	2016	Elsevier	experts	true, simulated	private company (not in the transport sector), simulated	static	2D flow map, 2D graduated symbol map, 3D flow map, line chart	2D+3D+1T	non-geospatial technique, 3D	compliant	mobility patterns	no
[193]	2016	Elsevier	experts	true	transport service, unspecified (taxi)	static, real-time	2D choropleth map, 3D colored area map, 3D dot map, 3D flow map, 3D graduated symbol map, 3D network map, 3D ordered network map, line chart, multiset histogram	2D+3D+nT	non-geospatial technique	compliant	public transportation use	no
[194]	2017	Elsevier	experts	true	research project (volunteer tracking), transport service	static	2D graduated symbol map, bar chart, tree	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (2)
[195]	2017	Elsevier	experts	true	phone operator, citizens (social media)	static	other	1T	not applicable	not compliant	mobility patterns	no
[196]	2018	Elsevier	experts	true, simulated	citizens (questionnaire), simulated	static	2D choropleth map	2D	none	not compliant	accessibility/travel time	no
[197]	2019	Elsevier	experts	true	citizens (social media), authorities	static	2D dot map, 2D flow map, 2D graduated symbol map, 2D ordered network map, line chart, histogram, heatmap	2D+nT	non-geospatial technique	not compliant	mobility patterns	no
[198]	2019	Elsevier	experts	true	authorities (cameras)	static	2D graduated symbol map, 2D network map, stream graph	2D+1T	symbol on GSM, non-geospatial technique	compliant	mobility patterns	yes (9)
[199]	2019	Elsevier	citizens	true	transport service	static	2D network map, bar chart, multi-layer ring, violin plot	2D+nT	none	not compliant	public transportation use, accessibility/travel time	yes (10)
[97]	2019	Elsevier	experts	true	unspecified (taxi)	static	2D flow map, bar chart, bubble chart, heatmap, stacked histogram	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[200]	2019	Elsevier	experts	true, simulated	citizens (volunteered tracking), simulated	static	2D flow map	2D	none	not compliant	mobility patterns	no
[201]	2020	Elsevier	experts	true, simulated	authorities, online api (Open Trip Planner), simulated	static	2D choropleth map, box plot, line chart	2D+nT	none	not compliant	accessibility/travel time	no
[98]	2011	Wiley	experts	true	unspecified	static	2D dot map, 2D network map	2D	none	not compliant	congestion	no
[202]	2013	Wiley	experts	true	private company (not in the transport sector)	static	2D dot map, 2D flow map, histogram	2D+1T	non-geospatial technique, animation	compliant	mobility patterns	yes (3)
[60]	2013	Wiley	experts	true	transport service	static	chord diagram	1T	not applicable	compliant	mobility patterns, public transportation use	no
[55]	2015	Wiley	experts	true	authorities (taxi)	static	2D flow map, 2D graduated symbol map	2D	animation	not compliant	mobility patterns, congestion	yes (unspecified)
[43]	2016	Wiley	experts	true	transport service	static	2D flow map, 2D graduated symbol map, sankey diagram	2D+1T	non-geospatial technique	compliant	mobility patterns	yes (5)
[203]	2010	Snowball analysis	experts	true	authorities, citizens (social media)	static	2D flow map, 2D graduated symbol map	2D	none	compliant	mobility patterns	no
[37]	2010	Snowball analysis	experts	true	authorities (sensors)	static	2D flow map, 2D graduated symbol map, 3D flow map	2D+3D	3D	not compliant	congestion	no
[204]	2011	Snowball analysis	experts	true	authorities	static	2D graduated symbol map, 3D dot map, line chart	2D+3D+1T	non-geospatial technique, 3D	compliant	congestion	no
[76]	2011	Snowball analysis	experts, citizens	true	private company (not in the transport sector), online api (government website)	static, real-time	2D flow map, 2D graduated symbol map, histogram	2D+1T	symbol on GSM, non-geospatial technique	compliant	mobility patterns	no
[82]	2012	Snowball analysis	experts	true	sensor network	static	2D flow map, 2D graduated symbol map, heatmap, line chart	2D+nT	symbol on GSM, non-geospatial technique	compliant	mobility patterns	no

Ref.	Year	Publish.	Target users	Data realness	Data source	Data availability	Visualization techniques	Architecture	Time representation	Compliance to mantra	Domain	User study conduct (participants)
[99]	2012	Snowball analysis	experts	true	transport service	static	2D graduated symbol map, gantt chart, line chart	2D+nT	non-geospatial technique	compliant	microsc. mov.	no
[205]	2012	Snowball analysis	experts	true	phone operator	static	2D dot map, 2D graduated symbol map, 2D network map, line chart, radar chart, scatterplot, stacked histogram	2D+nT	non-geospatial technique	not compliant	mobility patterns	no
[206]	2012	Snowball analysis	experts	true	authorities	static	heatmap	1T	not applicable	not compliant	mobility patterns	no
[207]	2014	Snowball analysis	experts	true	authorities	static	2D graduated symbol map, 3D flow map, stacked histogram	2D+3D+1T	non-geospatial technique, 3D	compliant	congestion	no
[208]	2015	Snowball analysis	experts	true	phone operator	static	2D colored area map, 2D dot map, 2D graduated symbol map, 3D graduated symbol map, line chart, radar chart	2D+3D+nT	non-geospatial technique, animation	compliant	mobility patterns	no
[92]	2015	Snowball analysis	experts	true	unspecified (taxi)	static	2D graduated symbol map, heatmap, histogram, stacked area chart	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[209]	2016	Snowball analysis	experts, citizens	true	unspecified (taxi)	static	2D dot map, 2D flow map, 2D network map, heatmap, parallel coordinates plot, parallel sets, scatterplot	2D+nT	non-geospatial technique	compliant	mobility patterns, anomaly detection, congestion	yes (17)
[210]	2016	Snowball analysis	experts	true	private company (not in the transport sector) (taxi)	static	2D graduated symbol map, discrete violin plot, heatmap, histogram, scatterplot	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (unspecified)
[211]	2017	Snowball analysis	experts	true	phone operator	static	2D flow map, 2D graduated symbol map, heatmap, histogram, parallel coordinates plot	2D+nT	non-geospatial technique	compliant	mobility patterns	no
[212]	2017	Snowball analysis	experts	true	private company (not in the transport sector)	static	2D choropleth map, 2D graduated symbol map, bar chart, line chart	2D+nT	non-geospatial technique	compliant	mobility patterns	yes (16)
[66]	2018	Snowball analysis	experts	true	transport service	static	2D flow map, 2D graduated symbol map, bullet chart, heatmap, line chart, radar chart, stacked chart	2D+nT	non-geospatial technique	compliant	public transportation use, congestion	no
[96]	2018	Snowball analysis	experts	true	online api (Baidu), unspecified (taxi)	static	2D choropleth map, 2D flow map, bubble chart, donut chart, heatmap, multiset bar chart, parallel coordinates plot, rose chart	2D+nT	non-geospatial technique	compliant	mobility patterns	no

TABLE VIII
FREQUENCY OF THE DATA SOURCES PER DOMAIN.

Domain	Citizens	Auth.	Transp.	Phone	Other PC	Research	API	IoT	Simul.
Mobility patterns	**17**	14	**16**	15	8	2	3	4	4
Congestion	3	**11**	7	0	3	4	1	8	7
Microscopic movements	0	2	2	0	2	2	0	**3**	2
Public transportation use	1	2	**10**	0	0	0	0	0	0
Accessibility/travel time	2	2	**4**	0	**3**	0	2	0	2
Accidents	1	**7**	0	0	0	1	0	2	1
Pollution	0	0	0	0	0	0	0	2	**4**
Anomaly detection	0	1	0	0	0	1	0	1	0
Route recommendation	0	0	1	0	0	0	0	0	0
Parking availability	1	0	0	0	0	0	0	1	0

TABLE IX
FREQUENCY OF THE VISUALIZATION ARCHITECTURES PER DOMAIN.

Domain	1T	nT	2D	2D+1T	2D+nT	3D	3D+1T	3D+nT	2D+3D	2D+3D+1T	2D+3D+nT
Mobility patterns	3	2	12	11	**37**	0	1	1	1	2	3
Congestion	1	1	**16**	3	12	2	0	0	1	3	1
Microscopic movements	0	0	**5**	2	**5**	1	0	0	0	0	0
Public transportation use	2	0	2	0	**5**	0	1	1	0	0	1
Accessibility/travel time	0	0	**4**	1	**5**	1	0	0	1	0	0
Accidents	0	0	1	**4**	**4**	1	0	0	0	0	0
Pollution	0	0	**2**	1	1	**2**	0	0	0	0	0
Anomaly detection	0	1	0	1	1	0	0	0	0	0	1
Route recommendation	0	0	0	0	**2**	0	0	0	0	0	0
Parking availability	0	0	0	1	1	0	0	0	0	0	0

TABLE X
FREQUENCY OF THE GEOSPATIAL VISUALIZATION TECHNIQUES PER DOMAIN.

Domain	Point-based map			Line-based map			Area-based map		
	DM	SM	GSM	NM	ONM	FM	CAM	OCM	CM
Mobility patterns		**56**			46			14	
	17	1	47	15	1	40	0	3	12
Congestion		27			**31**			1	
	10	0	20	8	7	21	0	1	0
Microscopic movements		**9**			**8**			0	
	4	0	6	3	0	6	0	0	0
Public transportation use		7			**8**			2	
	4	0	6	4	1	5	0	1	2
Accessibility/travel time		3			**7**			4	
	0	0	3	2	0	5	0	1	3
Accidents		**8**			6			0	
	4	0	5	1	3	3	0	0	0
Pollution		**4**			**3**			1	
	0	0	4	1	1	2	0	0	1
Anomaly detection		**2**			**3**			0	
	2	0	1	2	0	3	0	0	0
Route recommendation		**2**			1			0	
	0	0	2	0	0	1	0	0	0
Parking availability		**2**			0			0	
	0	0	2	0	0	0	0	0	0

Note: The totals of the three map subtypes might add to more than the frequency of the upper map type. For example, if an article uses a dot map and a graduated symbol map, each subtype would be incremented, whereas the count related to point-based maps would increment by only 1.

TABLE XI
FREQUENCY OF THE NON-GEOSPATIAL VISUALIZATION TECHNIQUES PER DOMAIN.

Domain	Heatmap	Line chart	Histogram	Scatterplot	Bar chart	PCP	Stacked hist.	N-L diagram
Mobility patterns	**28**	23	18	9	8	11	8	7
Congestion	**13**	9	6	7	3	4	6	1
Microscopic movements	**5**	**4**	2	**4**	1	1	2	0
Public transportation use	**4**	2	2	1	2	1	0	0
Accessibility/travel time	1	1	0	1	1	0	**2**	0
Accidents	**5**	**4**	3	**4**	1	1	0	0
Pollution	1	1	0	0	1	0	0	0
Anomaly detection	**5**	1	2	1	0	2	0	1
Route recommendation	0	0	0	0	0	1	2	0
Parking availability	0	1	1	0	1	0	0	0

TABLE XII
FREQUENCY OF THE VISUALIZATION ARCHITECTURES PER DATA SOURCE.

Data source	1T	nT	2D	2D+1T	2D+nT	3D	3D+1T	3D+nT	2D+3D	2D+3D+1T	2D+3D+nT
Citizens	1	1	**8**	4	**7**	0	1	1	1	0	1
Authorities	1	0	8	2	**16**	2	0	0	1	3	1
Transport service	3	0	5	1	**10**	1	1	2	0	0	1
Phone operator	1	0	1	3	**8**	0	0	0	0	1	1
Other private company	0	0	2	3	**8**	0	0	0	0	1	0
Research project	0	1	1	1	**3**	0	0	0	0	0	1
Internet of Things	0	2	4	3	**7**	0	0	0	0	0	0
Simulated	0	0	**8**	1	3	3	0	0	0	1	0

TABLE XIII
FREQUENCY OF THE GEOSPATIAL VISUALIZATION TECHNIQUES PER DATA SOURCE.

Data source	Point-based map	DM	SM	GSM	Line-based map	NM	ONM	FM	Area-based map	CAM	OCM	CM
Citizens	**17**	7	1	12	15	3	3	10	6	0	1	6
Authorities	**25**	8	0	21	21	5	3	17	5	0	1	4
Transport service	**15**	5	0	14	12	6	1	9	4	0	1	4
Phone operator	**13**	4	0	12	10	5	0	9	3	0	2	1
Other private company	9	3	0	7	**12**	1	1	11	1	0	0	1
Research project	**5**	1	0	5	**4**	0	0	4	1	0	1	0
Internet of Things	**9**	4	0	7	**9**	3	3	4	1	0	0	1
Simulated	**10**	4	0	7	**10**	4	0	7	2	0	0	2

Note: The totals of the three map subtypes might add to more than the frequency of the upper map type. For example, if an article uses a dot map and a graduated symbol map, each subtype would be incremented, whereas the count related to point-based maps would increment by only 1.

TABLE XIV
FREQUENCY OF THE NON-GEOSPATIAL VISUALIZATION TECHNIQUES PER DATA SOURCE.

Data source	Heatmap	Line chart	Histogram	Scatterplot	Bar chart	PCP	Stacked hist.	N-L diagram
Citizens	**8**	**7**	3	3	2	0	0	0
Authorities	**13**	10	6	9	3	4	4	2
Transport service	6	**8**	3	1	4	0	2	0
Phone operator	**5**	**5**	3	3	1	3	2	1
Other private company	**5**	3	**4**	3	3	1	2	2
Research project	**5**	**4**	1	1	2	1	1	1
Internet of Things	**5**	**5**	**6**	2	3	1	1	0
Simulated	2	**4**	1	1	0	0	0	0

TABLE XV
FREQUENCY OF THE VISUALIZATION ARCHITECTURES PER TARGET END-USER.

Target end-user	1T	nT	2D	2D+1T	2D+nT	3D	3D+1T	3D+nT	2D+3D	2D+3D+1T	2D+3D+nT
Citizens only	0	1	**3**	2	**3**	1	0	0	0	0	0
Experts only	5	4	24	13	**51**	4	2	1	1	5	5
Both citizens and experts	0	0	**6**	3	4	1	0	1	0	0	0
Unspecified	0	0	**4**	0	1	0	0	0	1	0	0

TABLE XVI
FREQUENCY OF THE GEOSPATIAL VISUALIZATION TECHNIQUES PER TARGET END-USER.

Target end-user	Point-based map			Line-based map			Area-based map		
	DM	SM	GSM	NM	ONM	FM	CAM	OCM	CM
Citizens only		**6**			**7**			0	
	4	0	3	4	1	3	0	0	0
Experts only		**78**			70			19	
	23	1	65	19	10	53	0	5	16
Both citizens and experts		**11**			**10**			1	
	5	0	8	2	0	9	0	1	0
Unspecified		**4**			**3**			2	
	1	0	4	1	0	2	0	0	2

Note: The totals of the three map subtypes might add to more than the frequency of the upper map type. For example, if an article uses a dot map and a graduated symbol map, each subtype would be incremented, whereas the count related to point-based maps would increment by only 1.

TABLE XVII
FREQUENCY OF THE NON-GEOSPATIAL VISUALIZATION TECHNIQUES PER TARGET END-USER.

Target end-user	Heatmap	Line chart	Histogram	Scatterplot	Bar chart	PCP	Stacked hist.	N-L diagram
Citizens only	**2**	1	0	1	**2**	0	**2**	0
Experts only	**43**	35	25	17	13	11	12	7
Both citizens and experts	**3**	**2**	1	1	1	**2**	0	0
Unspecified	0	1	1	1	0	1	0	0